Low-Energy UWB Transceiver Implementation For Smart Home Energy Management

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***Abstract*—This paper presents the design and implementation of an autonomous system for monitoring and managing the energy consumption in smart home applications. The work introduces a low-power Ultra-Wideband (UWB) transceiver, fully integrated into a smart home sensor node with web-services software infrastructure. This unique combination enables novel applications characterized by extreme low energy while maintaining interoperability between heterogeneous wireless sensor networks (WSN). A prototype version of the UWB system is implemented with a custom-designed transmitter fabricated in UMC 130nm CMOS technology and a discrete receiver. The proposed fully integrated UWB transmitter consumes 39μW at the pulse rate of 1Mbps. The complete integrated sensor node including the sensor and its interface, microcontroller and UWB transmitter achieves an energy consumption of 5.31nJ/bit, which is one order of magnitude lower than commercial wireless technologies for smart home applications.**

I. Introduction

The interest in the world's energy shortage raised the need for low energy consumption in buildings [1],[2]. The concern in many applications is to reduce the energy consumption and the CO_2 footprint in existing public buildings and spaces without performing serious construction works. This can be done by means of wireless sensor networks [3]. Usually, buildings are supplied with Building Management Systems (BMS) to control physical or environmental conditions such as temperature, humidity and illumination level. In order to increase the energy efficiency of such buildings, it is necessary to improve existing smart home solutions with new technologies such as WSNs and smart energy meters.

A major issue, when trying to integrate different technologies into a central home control system, is the heterogeneity of the devices that prevents interoperability. Various technologies use different communication protocols, programming models and user interfaces. An approach to overcome these heterogeneity issues is to provide abstractions to diverse standards at a higher layer, offering a uniform interface. As such, middleware can decrease the complexity to integrate different technologies into the control system. Moreover, wireless sensor nodes for energy consumption management need consume extremely low energy to guarantee lifetimes of multiple years on a single battery or scavenger. This limits the allowed energy consumption into a few nJ per bit. As the wireless radio is typically the major energy consumer of the complete sensor node, this paper will compare different air interface candidates for low-energy smart home WSN applications. Due to its asymmetrical energy consumption profile between transmitter and receiver, a pulsed-UWB-based system is selected as the most suitable radio technology. This paper will subsequently discuss the realized pulsed-UWB-based transceiver and its integration in the software infrastructure called LinkSmart middleware [3].

II. UWB hardware

A typical wireless sensor node includes a sensor and its interface, a controller block and a radio core for communication. Existing off-the-shelf commercial sensor nodes for smart home energy management applications, such as TelosB, STM300 and CC2530 are integrated into the LinkSmart middleware [3]. These sensor node solutions have a high energy consumption due to the use of energy-hungry protocols such as ZigBee. In Table I, different wireless standards are compared based on the energy-per-bit metric. In order to provide a wireless sensor node solution with high energy autonomy, hence broadening the application scope of WSNs for smart home applications, the pulsed-UWB technology is chosen. It is chosen because of its low-energy characteristics, its potential exploitation for localization in indoor environments and its robustness against interferers.

TABLE I. Comparison of energy consumption for different wireless standards

Standard	Energy-per-bit (nJ/bit)	Maximum bit rate (Mb/s)
ZigBee	296	0.250
Bluetooth	34	1
Wifi	130	54
UWB	5	100

Figure 1 depicts the complete implemented hardware system. At the sensor side, the physical information, e.g. the temperature, is converted to digital bits and then modulated in the UWB pulse generator and transmitted through the UWB antenna. At the receiver side, the energy detection receiver demodulates the data and uploads it to the middleware. The interface code for our UWB system resides in the middleware next to PC-gateway codes for other standards. The UWB transmitter is shown in Figure 3 (a). It consists of a 5th-derivative Guassian pulse generator [4]. The topology reduces the power consumption due to the digital-oriented transmitter architecture with low DC power and the lack of active circuitry for shaping the output pulse. The simulated circuit produces

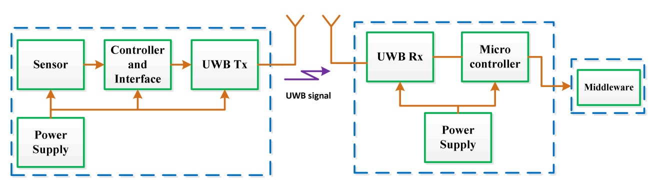

Fig. 1. Developed UWB system

a UWB pulse with 1ns width corresponding to a 1GHz bandwidth signal and a power consumption of 35.64μW for 1Mbps bit rate. At the transmitter side, the chip has been implemented in a 0.13μm CMOS process. At the receiver side, an energy detection topology is implemented which includes a low-noise amplifier, a power detector, a comparator and a microcontroller. This receiver extracts the envelop of the amplified signals, converts them to digital bits and wakes up a microcontroller from its low-power sleeping mode to process the data. The microcontroller then connects the transceiver to the middleware.

III. Software Infrastructure

In typical smart home applications, users prefer to access the environmental parameters measured by the sensor nodes via a hardware-independent interface at a high level. The LinkSmart middleware provides a remote connection utilizing a software interface called PC-Gateway (GW). For this UWB WSN, a particular interface has been written which adds interoperability to the system [3]. As shown in Figure 2, all the information coming from the WSNs, regardless of the communication protocols, hardware or network topology, is sent to a dedicated interface, that is the lowest layer of the proposed platform. At the application-client layer, the information is available to the end user and ready to be managed by him/her remotely. In this way, the system is able to deploy the new solution in buildings and public spaces by integrating them into the overall energy management system.

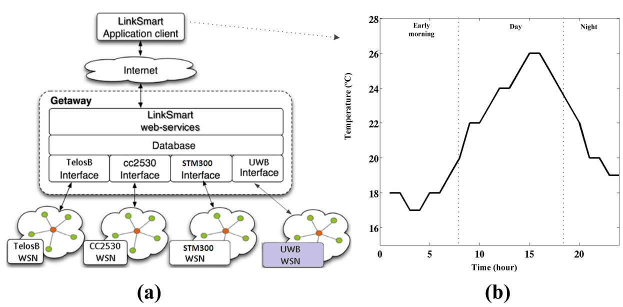

Fig. 2. (a) The software infrastructure layout and (b) measured temperature profile

IV. Measurement and Results

The fully integrated UWB sensor node and the receiver implemented on PCB are shown in Figure 4. The wireless link is validated in a real-life application setting, in which temperature information is transferred wirelessly to the receiver, after which the microcontroller sends data to the middleware through a serial link. A measured temperature profile for an office in 24 hours, available in the application-client layer, is shown in Figure 2. The generated measured UWB pulse and the die photograph are shown in Figure 3 (b) and (c), respectively. The pulse has 1.1ns width corresponding to a bandwidth of 909MHz and a Vpp equal to 180mV. The UWB transmitter consumes 39μW at a bit rate of 1Mbps. The receiver has a sensitivity of -67dBm with bit rate up to 1Mbps. The total sensor node energy consumption is 5.31nJ/bit. Table II compares this work with some other commercial products, demonstrating a ten times better energy efficiency. The low energy consumption of the introduced UWB technology enables completely autonomous, fully integrated sensor nodes for smart home energy management.

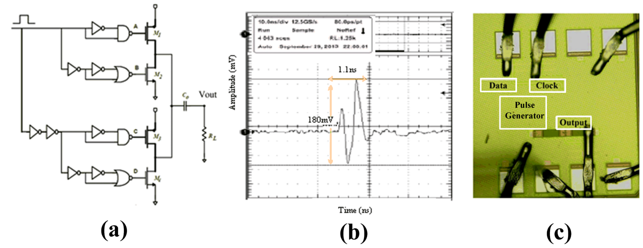

Fig. 3. (a) UWB pulse generator, (b) measured pulse and (c) die photograph

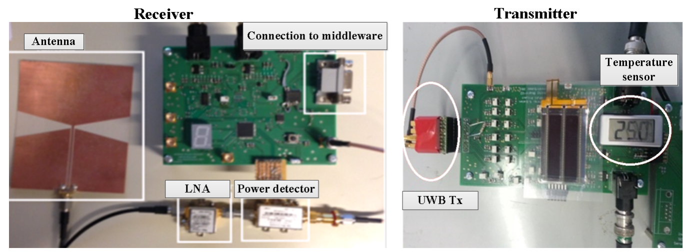

Fig. 4. Fully integrated UWB sensor node and receiver

V. Conclusion

The design and implementation of a low-energy UWB transceiver for monitoring and managing the energy consumption in a smart home application has been presented. The fully integrated UWB system has been implemented with a custom-designed transmitter fabricated in UMC 130nm CMOS technology. The total sensor node energy consumption is 5.31nJ/bit which is a ten times better energy efficiency compared to the commercial wireless technologies for smart home applications. The transceiver has been integrated in the middleware while a temperature sensor is utilized to measure the environmental temperature.

TABLE II. Comparison of the UWB sensor node with existing commercial products

Sensor node product	STM300	CC2530	TelosB	**This Work (UWB)**
Peak Power	50.4mW	87mW	17.4mW	**5.31mW**
Bitrate	125 kbps	250 kbps	250 kbps	**1 Mbps**
Energy/bit	403 nJ/bit	348 nJ/bit	69.6 nJ/bit	**5.31 nJ/bit**

VI. Acknowledgment

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